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FINAL

TECHNICAL REPORT

Under
AFOSR Grant 49620-92-J-0498

Nonlinear Dynamics Underlying Atmospheric Prediction

by

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I. INTRODUCTION

Under AFOSR grant 49620-92-J-0498, 11 papers have been published, 4 papers are in press, 2 papers are under revision for publication, 2 have been submitted and 2 are in preparation based on the full or partial support of AFOSR 49620-92-J-0498, as follows. These various papers include the work of several graduate students (including two Ph. D. students who have received their degrees).

An adjoint sensitivity study of blocking in a two-layer isentropic model, by X. Zou, A. Barcilon, I. M. Navon, J. Whitaker and D. G. Cacuci; *Mon. Wea. Rev.*, **121**, 2833–2875, 1993.

Domain decomposition and parallel processing of a finite-element model of the shallow-water equations, by I. M. Navon and Yihong Cai; *Computer Methods in Appl. Mech.*, **106**, 179–212, 1993.

An efficient method for investigating flow evolution in shear layers, by Y. Chang, A. Barcilon and S. Blumsack; *Geophys. Astrophys. Fluid Dyn.*, **76**, 73–93, 1995.

Low frequency oscillations of forced barotropic flow, by T. R. Nathan and A. Barcilon; *J. Atmos. Sci.*, **51**, 582–588, 1994.

The global atmospheric response to localized time varying forcing: Zonally uniform basic states, by L. Li and T. R. Nathan; *J. Atmos. Sci.*, **51**, 3412–3426, 1994.

Variational data assimilation with a variable resolution finite-element shallow-water equations model, by K. Zhu, I. M. Navon and X. Zou; *Mon. Wea. Rev.*, **122**, 946–965, 1994.

Parallel domain decomposed preconditioners for the finite element shallow-water flow modeling, by Yihong Cai and I. M. Navon; *Proceedings of the Seventh International Conference on Domain Decomposition Methods for Scientific and Engineering Computing*, edited by D. E. Keyes and J. Xu, Series on Contemporary Mathematics, **180**, American Mathematical Society, 471–476, 1994.

Iterative domain decomposition algorithms: Theory and applications, by Yihong Cai and I. M. Navon; **High Performance Comp. in the Geosci.**, edited by F. X. Le Dimet, NATO Advanced Research Workshop, Centre de Physique, Les Houches, France, 21–25, June 1993, NATO Advanced science Institute Series: C, Mathematical and Physical Sciences, 462, Kluwer Academic publishers B. V., 284 pp., 81–106, 1995.

Low frequency variability and wavenumber selection in models with zonally-symmetric forcing, by J. Whitaker and A. Barcilon, *J. Atmos. Sci.*, **52**, 491–503, 1995.

Parallel block preconditioning techniques for the numerical simulation of shallow-water flow using finite-element methods, by Yihong Cai and I. M. Navon; *J. Comp. Phys.*, **122**, 39–50, 1995.

Low frequency oscillations in turbulent Rayleigh-Benard convection: Laboratory experiments, by R. Krishnamurti; *J. Fluid Dyn. Res.*, **16**, 87–108, 1995.

Forced baroclinic wave dynamics at minimum critical shear: Potential vorticity homogenization, vacillation, and equilibration, by M. Parlange and T. R. Nathan; in press, *J. Atmos. Sci.*, 1996.

The effects of low frequency tropical forcing on intraseasonal tropical-extratropical interactions, by L. Li and T. R. Nathan; in press, *J. Atmos. Sci.*, 1996.

Low frequency dynamics in a two-layer model with simple topography, by A. Barcilon and D. Bachiochi; in press, *J. Atmos. Sci.*, 1996.

Use of empirical orthogonal functions (EOFs) as basis functions in numerical prediction models, by Y. Chang, R. Pfeffer and A. Barcilon; in press, *J. Atmos. Sci.*, 1996.

Low frequency oscillations in turbulent Rayleigh-Benard convection: A scavenging plume model, by R. Krishnamurti; accepted pending revisions by *J. Fluid Dyn. Res.*, 1996.

Flow over topography in a two-layer model, by D. Bachiochi and A. Barcilon; accepted pending revisions by *J. Atmos. Sci.*, 1996.

Stability of a compressible shear flow, by W. Blumen and A. Barcion; submitted to *Dyn. of Atmos. and Oceans*, 1996.

Nonlinear spatial baroclinic instability in slowly varying zonal flow, by T. R. Nathan; submitted to *Dyn. of Atmos. and Oceans*, 1996.

Convection induced by selective absorption of radiation: A laboratory model of conditional instability, by R. Krishnamurti; to be submitted to *J. Atmos. Sci.*, 1996.

LADFEUDX — A FORTRAN program for variational data assimilation with a finite-element shallow-water equations model, by K. Zhu, I. M. Navon and X. Zou; to be submitted to *Comp. in Math. with Appl.*, 1996.

Ph. D. Dissertations

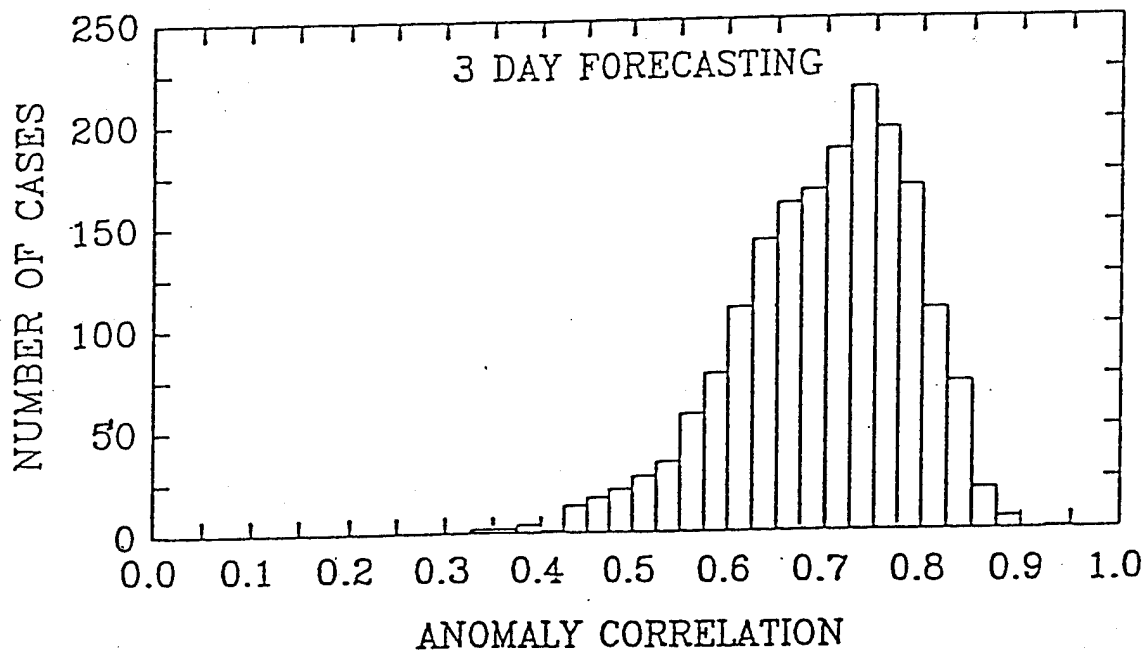
Yihong Cai, 1994: Domain decomposition algorithms and parallel composition techniques for the numerical solution of PDEs with applications to the finite element shallow-water flow. Ph. D. Dissertation, Florida State University, Tallahassee, FL 32306-3017.

Yehui Chang, 1994: Use of empirical orthogonal functions (EOFs) as basis functions in numerical prediction models. Ph. D. Dissertation, Florida State University, Tallahassee, FL 32306-3017.

2. RESEARCH HIGHLIGHTS

A. Numerical Weather Prediction Using EOFs

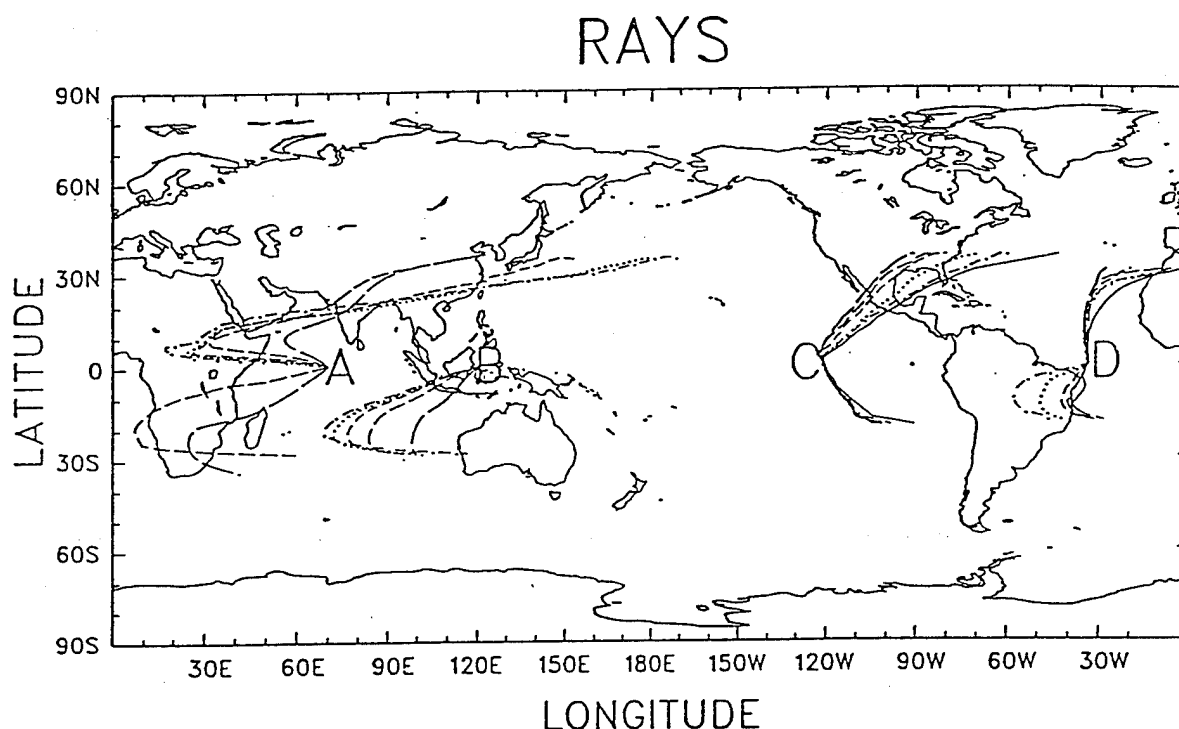
Drs. Barcilon and Pfeffer, collaborating with former student Yehui Chang, have demonstrated the usefulness of a truncated system of EOFs as basis functions in numerical weather prediction (Chang, Pfeffer and Barcilon, 1996). The EOFs were constructed from the complex spherical harmonic coefficients of a spectral model. The spectral model with 4 meteorological variables (stream function, velocity potential, layer thickness and vertical motion) and T-31 truncation consists of 3104 ordinary differential equations in 3104 unknowns. Since most of the variance in an EOF representation is compressed into a small number of PCs, the system of equations in which the spherical harmonics are replaced by their PC representation was truncated to 600 ordinary differential equations in 600 unknowns (4 variables, each represented by 150 PCs with the largest variance). A key result of their study is shown in Fig. 1, which gives the distribution of anomaly correlations between the forecast and the verification fields in both the lower and upper layers for 1800 three-day numerical predictions. We regard this as very promising, since these anomaly correlations are equal to or better than most models for three-day forecasting of meteorological variables in both the lower and upper atmosphere.



B. Low Frequency Dynamics and Predictability

Under the present grant, Dr. Terrence R. Nathan and his student Long Li have demonstrated that localized, low frequency tropical forcing can have a significant impact on the extratropical circulation. This impact is found to depend crucially on the frequency of the forcing

and the structure of the background state. The details of their work are contained in two papers by Li and Nathan (1994, 1996), in which they examine the extratropical response to localized forcing using a linearized, non-divergent barotropic model on a sphere. Their analysis based on WKB and ray tracing methods reveals that, in contrast to stationary Rossby waves, low frequency Rossby waves can propagate through the tropical easterlies into the mid latitudes. They find that the difference between the stationary and low frequency ray paths is proportional to the forcing frequency and inversely proportional to the cube of the zonal wave number. Moreover, the ability of the forced waves to maintain their strength well into middle latitudes depends on their meridional wave scale and poleward group velocity, both of which are functions of the slowly varying background flow. Fig. 2, from their second paper, gives an example of the ray paths of wavetrains with periods of 10 days (long dashed), 20 days (medium dashed), 30 days (short dashed), 40 days (dotted), 50 days (dash-dotted) and stationary (solid) for zonal wave number 3. The sources, A, B, C and D are located at the equator and 70°E, 120°E, 120°W and 30°W, respectively.



C. Nonlinear Dynamics of Baroclinic Waves

In their collaborative work, Drs. Nathan and M. Parlange, (Parlange and Nathan, 1996) have shown that forcing analogous to land-sea heating contrasts can produce oscillatory behavior and disrupt the homogenization of potential vorticity (PV), and thereby prevent the formation of strong vortices. In particular, they examine the response of a nonlinear baroclinic system near marginal equilibrium to zonally varying PV forcing. Their key finding is that, for sufficiently strong forcing of a higher harmonic of the fundamental unstable mode, the system can exhibit either a steady state or a vacillatory response. The former leads to strong vortex formation and the latter prevents it.

D. Nonlinear Spatial Baroclinic Instability in Slowly Varying Zonal Flow

In a recent theoretical study (Nathan, 1996), supported in part by AFOSR Grant 49620-92-J-0498, Dr. Nathan has discovered a major difference between the locations of storm tracks predicted by linear and nonlinear theory. For a basic state jet flow possessing a locally unstable region, the weakly nonlinear solution yields a maximum amplitude that is located near the region of maximum baroclinicity and *substantially upstream of the maximum amplitude obtained from the linear theory*. The difference between the linear and nonlinear solutions is due to the time-averaged wave fluxes becoming large enough in the nonlinear problem to stabilize the flow prior to reaching the jet center, where the basic state baroclinicity and locally computed linear growth rate are maximized.

E. Low Frequency Variability in the Absence of Forcing

Dr. Barcilon, in collaboration with his former student, Dr. Jeffrey Whitaker, have used a two-layer quasi-geostrophic model with no zonal asymmetries to study low frequency atmospheric variability in the absence of external forcing (Whitaker and Barcilon, 1995), which is an important part of Southern Hemisphere atmospheric dynamics. Contrary to what had been the conventional wisdom prior to their work, they demonstrate that upscale nonlinear energy transfer *is not the dominant process* maintaining the amplitude of the most energetic wave. Instead, this wave, which is located at the boundary between the Rossby wave regime and the baroclinic regime, and which dominates the low frequency spectrum, grows baroclinically and is the wave that loses the least energy via nonlinear transfers. Drs. Barcilon and Whitaker have confirmed this behavior with the use of a primitive equation model in spherical geometry. The robust nature of this result gives further support to the conclusion that this is an important mechanism of atmospheric variability.

F. Rotating Convection

In previous convection studies, Dr. Ruby Krishnamurti and her colleagues and students (Krishnamurti, Krishnamurti and Bedi, 1989; Krishnamurti and Zhu, 1991) found that laboratory studies showing counter-gradient momentum fluxes could be used to parameterize the effects of fair weather cumulus on the wind field in the tropics, and thereby improve the predictions made by a global spectral model over the tropics. The primary new result of her convection studies under AFOSR Grant 49620-92-J-0498 has been the discovery of tilted plumes in *rotating* Rayleigh-Benard convection (Krishnamurti 1995). Although tilted plumes had been discovered in non-rotating convection, and used to improve NWP in the tropics, they were totally unexpected for rotating flows where, at least for high rotation rates, numerical simulations had always shown untilted vertical columnar plumes, and previous laboratory investigators had never reported observing tilted plumes.

Dr. Krishnamurti's observations were made in a rotating annulus of fluid uniformly and steadily heated from below and cooled from above. Unlike the non-rotating case, in which the plumes tilted from the lower left to the upper right, or from the lower right to the upper left, depending on the initial conditions at the onset of tilted flows, the plumes all tilt in only one sense in the rotating case, namely, from lower left to upper right as viewed from outside the apparatus,

with counterclockwise rotation. These results were tested with many different initial conditions (such as heating/cooling before spinning up the apparatus, or spinning up to solid body rotation before heating/cooling). In every case, the tilt was from lower left to upper right. Dr. Krishnamurti's explanation for this result is as follows:

With centrifugal force included, the effective gravity is not parallel to the rotation vector, but has a radially outward component. Thus, cooled fluid parcels, falling in the direction of the effective gravity travel to larger mean radius and, insofar as they conserve momentum, must slow down in their azimuthal motion. Consequently, they lag behind. Likewise, heated parcels rise parallel to the effective gravity to smaller mean radius and thus speed up. The net result of these slanted motions is to develop the observed tilt.

The important consequence of tilted convection is that the convective plumes now transport horizontal momentum as well as heat vertically. This transport must induce shear flow (in meteorological terminology, westerlies aloft and easterlies below). Fig. 3 shows examples of Dr. Krishnamurti's experimental convection plumes with both counterclockwise and clockwise rotation.

G. Moist Convection

The other important development in convection under the present grant has been Dr. Krishnamurti's successful simulation of the release of latent heat of condensation in moist convection by virtue of the selective absorption of radiation.

The fluid in the experiment is stably stratified by heating from above and cooling from below, but convects because of the internal heat sources. *The location of the internal heating is governed by the fluid flow itself, as in the atmosphere.* This is accomplished by passing orange light from a sodium vapor lamp downward through a tank of water containing a small amount of thymol blue. In its neutral state, the thymol blue makes the water appear orange, and the absorption of the orange light passing through it is negligible. In the present arrangement, the working fluid acts as a very weak electrolyte; its lower boundary acts as the positive electrode connected to a 9 volt battery. Near this boundary there is an excess of hydroxyl ions, which make the water dark blue. When the orange light from the sodium lamp reaches the bottom of the fluid, it is strongly absorbed and the fluid is thereby heated. Instability in this heated layer causes blue fluid to rise. As long as it remains blue, it continues to be heated and to rise. Thus, the internal heat source is only in the rising and not in the sinking plumes, and, as such, simulates the effects of latent heating in the atmosphere.

H. Inverse Problems Using Optimal Control

Dr. Michael Navon and his graduate students and colleagues (Zhu, Navon and Zou, 1994) have successfully applied optimal control of partial differential equations discretized by finite element methods to a limited area shallow water equations model used in atmospheric studies. This work required the derivation of the adjoint of such discrete operations as h and p -adaptivity, enrichment and de-enrichment of mesh nodes based on a posteriori error estimates. These methods significantly improve the predictability of numerical models and can be applied also to a much

broader range of practical problems such as reservoir modeling and nonlinear visco-elasticity. The transfer of this technology to other areas and groups is discussed in Section 3 of this report.

I. Domain Decomposition and Parallel Processing

Together with his student Yihong Cai, Dr. Navon has developed methodologies for domain decomposition and parallel processing of a finite element model of the shallow water equations with relevant preconditioning. This work, published in three papers (Navon and Cai, 1993; Cai and Navon, 1995a, 1995b) involves new approaches for parallel block preconditioning and new approaches in domain decomposition of the shallow water equations discretized by finite element methods. It also involves the synergistic use of novel iterative methods for systems of non-symmetric algebraic equations combined with preconditioning and domain decomposition portable to high performance parallel computer architectures. The transfer of this technology to other areas and groups is discussed in Section 3 of this report.

3. TECHNICAL TRANSITIONS

Technical transitions have taken place mainly in the areas in which new numerical techniques and algorithms have been developed under AFOSR Grant 49620-92-J- 0498.

In particular, Dr. Navon's approach to the use of optimal control of partial differential equations discretized by finite element methods now serves as the foundation for using the Tinsley Oden group PHLEX h - p adaptive finite element software and adapting it to the solution of inverse problems such as optimal control of distributed parameters, parameter estimation and sensitivity analysis. The research by Zhu, Navon and Zou (1994) now serves as the basis of a joint effort of Dr. Navon with the Comco Research Company under the supervision of Prof. Tinsley Oden.

The work carried out by Navon and Cai (1993) and Cai and Navon (1995a, b) is now being applied in the Department of Chemical Engineering at MIT by Professor Brown and Dr. Cai, as well as by a doctoral student at Columbia University.

The two-layer isentropic model and its adjoint and tangent linear models developed during collaborative research by Drs. Zou, Navon, Barcilon and others were given to Prof. Guoxiong Wu at the Institute of Atmospheric Physics, Academia Sinica in China, who has, in recent years, given us data and programs for use in our research that he developed. The purpose of this transfer was to show them how to develop a tangent linear and adjoint model of a spectral model and use them for sensitivity studies.